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# Towards an Optimal Motor Mounting Bracket Using Topology Optimization Combined with Sustainability and Manufacturing Cost Analysis

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**Abstract**

The engine is the most important component of a vehicle. It attaches to the main frame via the engine mounting bracket which supports weight and operating loads. The engine mount therefore plays a crucial role in the durability and comfort of the vehicle. This article contributes to the search for the most optimal model from the point of view of resistance, environmental impact, and manufacturing cost. This involves, on the one hand, optimizing the support by reducing its initial mass by 30%, and on the other hand, seeking suitable material and manufacturing process with the least environmental impact. To this end, topology optimization will be combined with an environmental assessment and a manufacturing cost analysis. Four materials will be tested and evaluated. Finally, a cost analysis will present a comparison between a conventional process and 3D printing.

**Keywords**

Engine mount; Topology optimization; Numerical simulation; Sustainability; Manufacturing; Costing analysis.

## Introduction

In the automotive industry, engineers seek to manufacture high-performance vehicles with less environmental impact and optimal cost. The use of structural optimization allows a considerable gain in mass and volume (Christensen & Klarbring, 2008). Over the past two decades, topology optimization has offered the best results under optimal conditions by preserving the external contour of the part (Wu et al., 2021; Fihri-Fassi et al., 2021; Liu et al., 2018; Bendsøe & Sigmund, 2004; Bender & Barari, 2019; Pragana et al., 2021; Doutre et al., 2015).

A brief review of the literature on topology optimization shows that many complex shapes resulting from this tool have become easily manufactured by additive manufacturing (Doutre et al., 2015; Bhatia & Sehgal, 2023; Li et al., 2018). Jun Wu et al., (2021) discuss different topology optimization methods used in the mechanical (Zhao et al., 2015). Umesh S Ghorpade et al. (2013) and V.K. Kurkute et al. (2022) present a study of engine support, in order to select the suitable material.

Zhou et al. (2022) show that 3D printing offers more possibilities for manufacturing complex shapes. Gulnaaz Rasiya et al. (2021) and Khademhosseini et al. (2019) highlighted the growing use of additive manufacturing in the automotive and aerospace industries. P.A.F. Pragana et al. (2021) summarizes some hybrid additive manufacturing processes of metals. On the other hand, an interesting review of sustainability perspectives for additive and subtractive manufacturing can be found in (Jayawardane et al., 2023; Ourihi et al., 2021; Duriez et al., 2022; Colorado et al., 2020).

In this context, this work presents a contribution to the development of a method involving eco-design, topology optimization, and additive manufacturing to offer an optimal ecological product from the design stage. As a case study, the approach will be applied to an engine mounting bracket.

## Objectives and methodology

Figure 1 shows the methodology used in this study. The first step is to design the motor mount using CATIA. Second, perform static analysis through simula-

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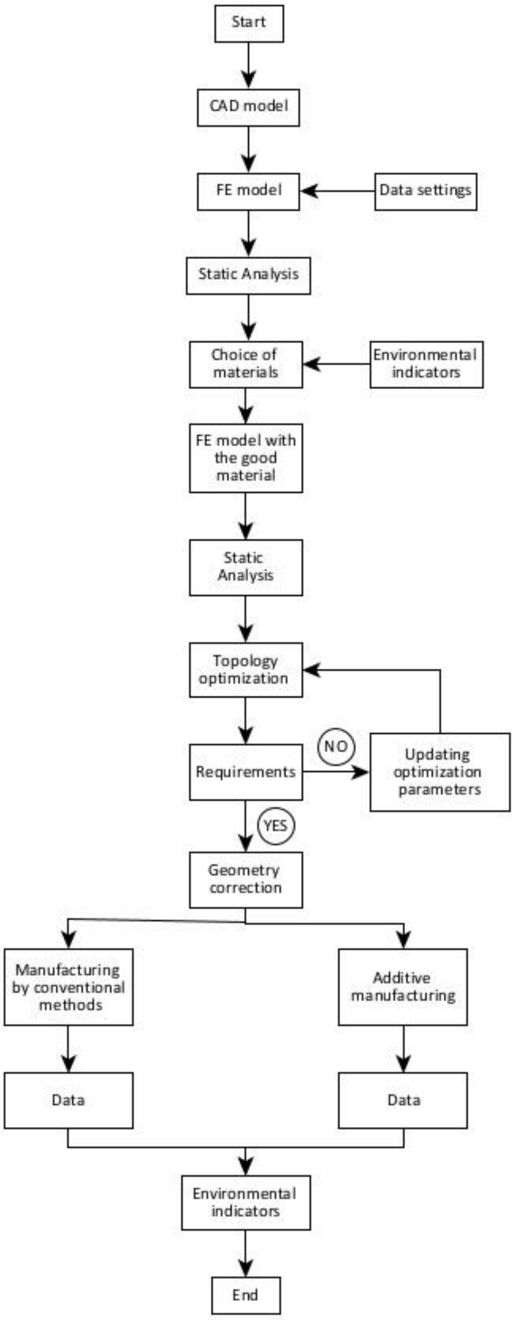


Fig. 1. Methodology

tions with Abaqus CAE (ABAQUS/TOSCA, 2023). Afterward, apply the topology optimization on the initial part. The next step is to choose between a conventional manufacturing method or additive manufacturing. Next, a cost analysis will be performed in SOLIDWORKS (3D CAD Design Software. SOLIDWORKS (2021)). Finally, we perform a sustainability analysis (https://ecodesign.ma, 2023; Ecodesign Studio, 2023) and a final decision will be made.

## Case study modeling

The engine mounting bracket chosen is apply to Peugeot 206 car (Fig. 2) (Ghorpade et al., 2013). In general, an engine bracket is essentially made of two materials: rubber and metal. The rubber absorbs vibrations and shocks, and the metal supports loads.

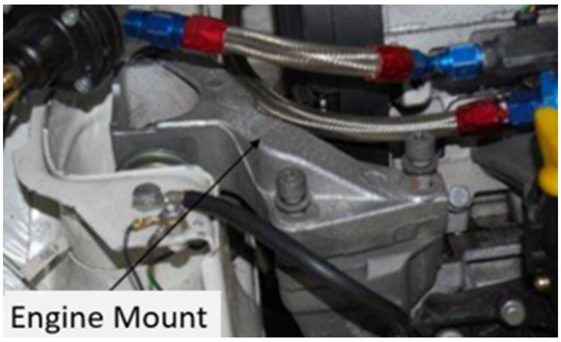


Fig. 2. Engine mount

For the static analysis, four materials will be tested: mild steel, aluminum alloy, magnesium alloy and cast iron (Table 1).

Figures 3 and 4 shows the first design of engine bracket.

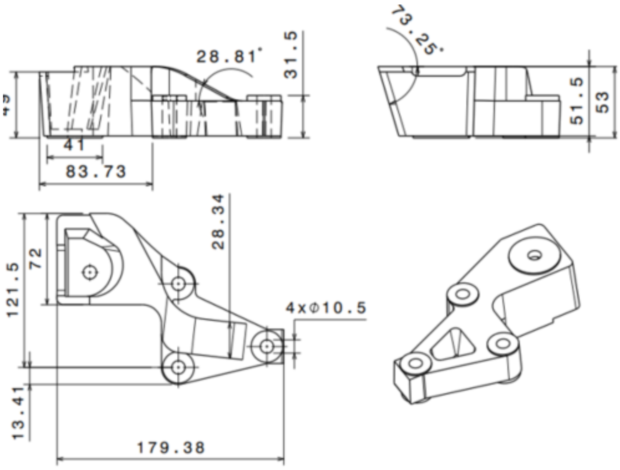


Fig. 3. Drafting of Engine Bracket

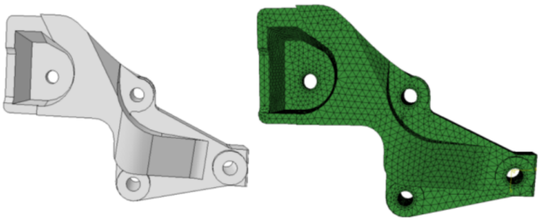


Fig. 4. 3D part and Solid mesh for the engine mount

Table 1
Materials and mechanical proprieties

| Mechanical properties | Cast iron | Aluminum alloy | Magnesium alloy EQ-21A-T6 | Mild steel |
|---|---|---|---|---|
| E (MPa) | 120 000 | 71 000 | 45 000 | 210 000 |
| v | 0.28 | 0.33 | 0.35 | 0.3 |
| d (t/mm$^3$) | 7.2E–9 | 2.77E–9 | 1.81E–9 | 7.89E–9 |
| Re (MPa) | 130 | 280 | 193 | 370 |
| Rm (MPa) | 220 | 310 | 234 | 440 |

Figure 5 shows Load and boundary conditions of the bracket applied via a multi-point constraint “MPC” for each hole.

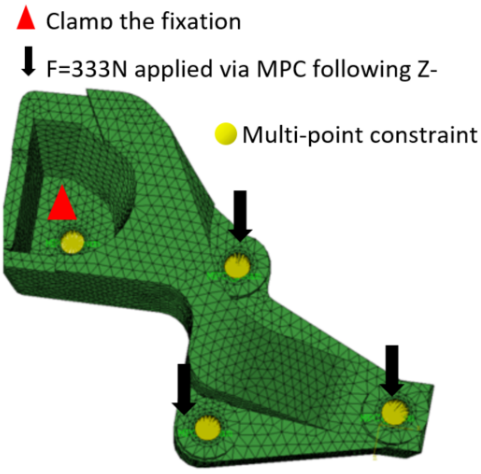


Fig. 5. Loads and boundary conditions

## Static analysis

Linear static analysis is used to evaluate the mechanical strength of the part in the elastic domain. The fundamental principle of dynamics is defined by (1):

$$\begin{aligned} \rho\frac{d^2\vec{u}}{dt^2} + \operatorname{div}(\sigma) - \vec{f^s} &= \vec{0} \quad \Omega \\ \vec{U} &= \vec{U}_d \quad \partial_1\Omega \\ \sigma\vec{n} &= \vec{F}_d \quad \partial_2\Omega \end{aligned} \tag{1}$$

with: $f^s$ – forces, $\rho$ – material density, $\vec{u}$ – displacement vector, $\sigma$ – stress tensor.

For a static analysis, equation (1) becomes:

$$[K]\{U\} = \{F\} \tag{2}$$

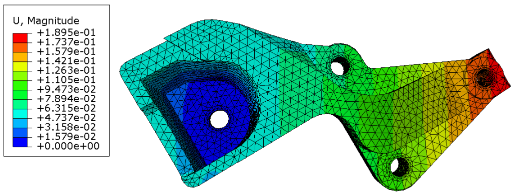
where $[K]$ is the global stiffness matrix, $\{U\}$ – displacement vector and $\{F\}$ – the global vector of the stresses.

For a case of a diagonalization of the stress tensor (3), Von Mises stress is:

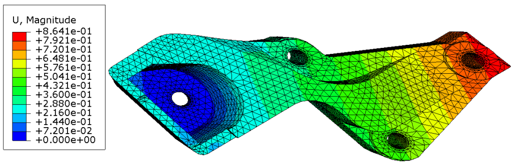
$$\sigma_{\text{VM}} = \frac{1}{2}\sqrt{(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2} \tag{3}$$

The global displacement results for the engine bracket are shown in Figures 6a–6d.

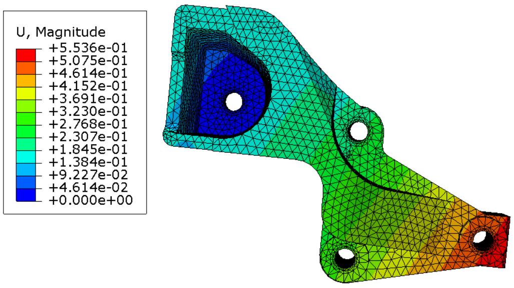
The Von Mises stress results are shown in Figures 7a–7d.



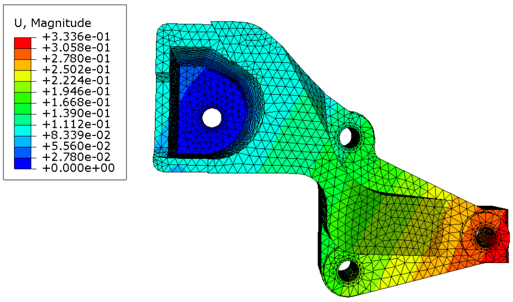
(a) Global displacement of a mild steel engine support



(b) Global displacement of a magnesium alloy engine support

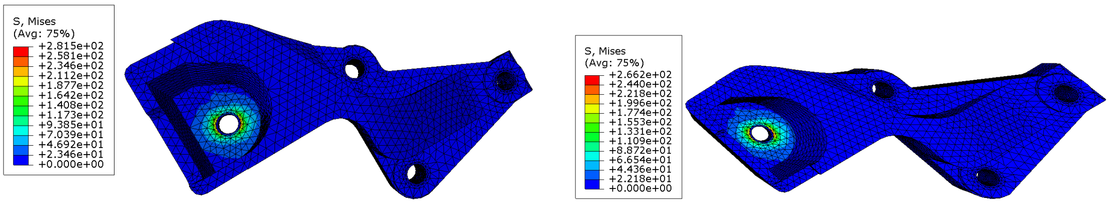


(c) Global displacement of an aluminum alloy engine support

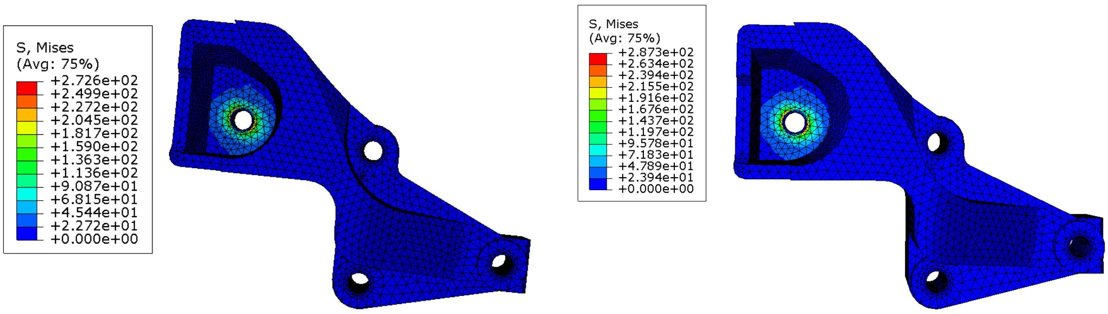


(d) Global displacement of a cast iron engine support

Fig. 6. Global displacement results for the engine bracket



(a) Von Mises stress of a mild steel engine support (b) Von Mises stress of a magnesium alloy engine mount



(c) Von Mises stress of an aluminum alloy engine mount (d) Von Mises stress of a cast iron engine mount

Fig. 7. Von Mises stress results

## Choice of materials

The final choice of material depends not only on the numerical results obtained but also on environmental indicators. These are evaluated during the life cycle of the product. Life Cycle Analysis (LCA) is a standardized method for developing a global, multi-criteria assessment of the environmental impacts of a product. The "LCA" includes raw material, manufacturing, use, transportation and end of life. We focus on the raw materials in Tables 2 and 3. Four materials will be evaluated.

Table 3 shows that the maximum stress for gray cast iron and magnesium alloy is greater than the respective yield strength of these two materials. From a strength point of view, the final choice is between aluminum alloy and mild steel. Compared to alu-

Table 2
Environmental impact assessment of materials

| Environmental indicators | Magnesium alloy – 0.566 kg | Cast iron – 2.25 kg | Non-alloy steel Profile 0.566 kg | Aluminum EN AW 5083 AlMg$_{4.5}$Mn$_{0.7}$ Profile 0.866 kg | Aluminium EN AW 2017A AICu$_4$MgSi Profile – 0.866 kg |
|---|---|---|---|---|---|
| Climate change (kg CO$_2$ eq.) | 75.844 | 3.15 | 3.3592 | 12.7302 | 10.392 |
| Resource depletion (kg eq. Sb) | 0.0513928 | 0.03105 | 0.0226993 | 0.060187 | 0.0589746 |
| Air acidification (kg SO$_2$ eq.) | 0.0247342 | 0.01089 | 0.0094601 | 0.0487558 | 0.052826 |
| Water pollution (m$^3$) | 2.09986 | 2.133 | 0.087191 | 3.68916 | 3.77576 |
| Air pollution (m$^3$) | 1714.98 | 1320.75 | 494 | 1853.24 | 1983.14 |
| Ozone depletion (kg CFC-11 eq.) | 5.9996E–07 | 1.134E–07 | 1.22265E–07 | 6.30448E–07 | 6.13994E–07 |
| Photochemical ozone formation (kg C$_2$H$_4$ eq.) | 0.00437518 | 0.00195975 | 0.00143013 | 0.00413948 | 0.00414814 |
| Eutrophication (kg PO43-eq.) | 0.00513928 | 0.00176625 | 0.00078793 | 0.00446856 | 0.00659026 |
| Ecotoxicity (fresh water) (UCTe) | 0.0044997 | 0.00170775 | 0.0023712 | 0.0098724 | 0.0105652 |

Table 2 [cont.]

| Environmental indicators | Magnesium alloy – 0.566 kg | Cast iron – 2.25 kg | Non-alloy steel Profile 0.566 kg | Aluminum EN AW 5083 $AlMg_{4.5}Mn_{0.7}$ Profile 0.866 kg | Aluminium EN AW 2017A $AICu_4MgSi$ Profile – 0.866 kg |
|---|---|---|---|---|---|
| Human toxicity (carcinogenic) (UCTh) | 8.9428E–10 | 6.885E–10 | 0 | 5.1527E–10 | 4.9795E–10 |
| Human toxicity (non-carcinogenic) (UCTh) | 1.11502E–09 | 8.775E–11 | 0 | 1.49818E–09 | 7.98452E–09 |
| Water consumption (1) | 303.376 | 25.65 | 5.9774 | 52.826 | 43.3 |
| Total primary energy (MJ) | 215.646 | 42.525 | 37.297 | 171.468 | 163.674 |
| Renewable energy (MJ) | 87.73 | 1.28025 | 1.50917 | 31.8688 | 28.7512 |
| Non- renewable energy (MJ) | 172.064 | 40.05 | 36.556 | 140.292 | 135.096 |
| Inert waste (Kg) | 1.78856 | 1.6875 | 6.3232 | 2.06108 | 2.67594 |
| Non- hazardous waste (Kg) | 0.201496 | 0.25875 | 0.155363 | 1.30766 | 1.32498 |
| Hazardous waste (Kg) | 0.080938 | 0.0010395 | 0.070889 | 0.00735234 | 0.00429536 |
| Radioactive waste (Kg) | 0.00202628 | 0.00016965 | 4.199E–05 | 0.000825298 | 0.00076208 |
| Single score (Points) | 3.94502 | 0.40275 | 0.29146 | 1.05652 | 0.9526 |

Table 3
Comparison between four materials

| Criterion | Cast iron | Aluminum alloy | Magnesium alloy | Mild steel |
|---|---|---|---|---|
| V. Misess stress (MPa) $<$ Re | 287.3 MPa | 272.6 MPa | 266.2 MPa | 281.5 MPa |
| Global displacement (mm) | 0.33 mm | 0.55 mm | 0.86 mm | 0.18 mm |
| Environmental indicator (Single score in Points) | 0.40275 points | 0.9526 points | 3.94502 points | 0.29146 points |
| Mass (Kg) | 2.25 | 0.866 Kg | 0.566 Kg | 2.46 Kg |

minum alloy, steel has the advantage of being more resistant and having less environmental impact. Therefore, the best material to use remains steel. The next section will be dedicated to the topology optimization approach.

## Topology optimization

A topology optimization problem can be defined mathematically as follows (Christensen & Klarbring, 2008; 3D CAD Design Software, 2021).

$$\text{Minimize } f(x,y) \text{ with respect to } x \text{ and } y$$

$$\text{subject to } \begin{cases} \text{design constraints on } x \text{ and} \\ \text{behavioral constraints on } y \\ \text{equilibrium constraint} \end{cases} \tag{4}$$

The present study considers, the strain energy as objective function, and saving 30% of the initial volume as the constraint function. Figure 8 shows the optimized support.

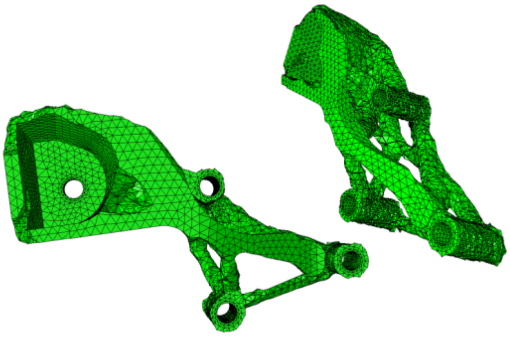


Fig. 8. The engine mounting bracket after applying topology optimization

The Von Mises stress and displacement for the optimized support are shown in Figures 9 and 10.

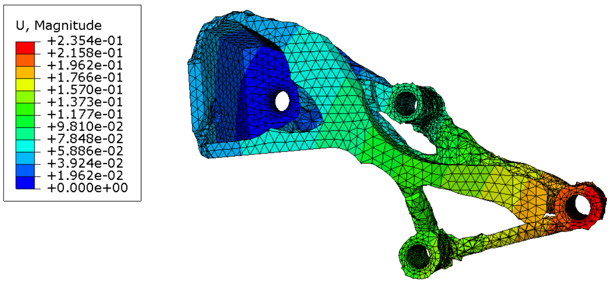


Fig. 9. Global displacement of a steel optimized engine mount

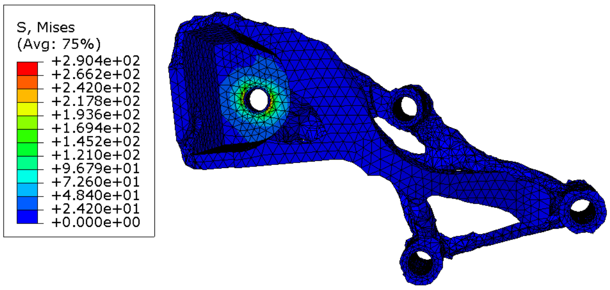


Fig. 10. Von Mises stress of a steel optimized engine mount

## Choice of manufacturing process

This section presents the environmental impact and cost analysis of the manufacturing process that can be used. Three manufacturing methods will be compared: machining, molding, and 3D printing.

For the life cycle analysis, the parameters used are the material "AISI Steel", the region "Europe", the lifespan "20 years" and transport will be by truck. At the end of its life, 25% will be recycled, 24% incinerated and 51% landfilled. The environmental indicators observed are: carbon footprint, total energy consumed, air acidification, water eutrophication and the financial impact of the material used (Table 4).

Table 4 shows that milling and sand casting are similar and therefore can be used.

Table 5 presents a costing analysis based on database of costing application in SolidWorks (3D CAD Design Software. SOLIDWORKS (2021)).

Casting is the least expensive process compared to machining and 3D printing. However, 3D printing remains the most suitable process for the part optimized from a quality point of view. Given the complexity of the geometry, the optimized shape cannot be manufactured by machining.

Table 4
Environmental impact for Manufacture of the support by sand molding or milling

| Manufacturing methods | Sand casting | | Machining: Milling | |
|---|---|---|---|---|
| Criterion | Initial part | Optimized part | Initial part | Optimized part |
| Carbon footprint (Kg.eq.$CO_2$) | 12 | 4.1 | 10 | 2.8 |
| Total energy consumed (MJ) | 180 | 61 | 120 | 36 |
| Air acidification (Kg.eq.$SOs_2$) | 0.051 | 0.018 | 0.04 | 0.011 |
| Water eutrophication (Kg.eq.$PO_2$) | 3.9E–3 | 1.3E–3 | 3.9E–3 | 1.E–3 |
| Financial impact of the material (USD) | 1.1 | 0.4 | 1.1 | 0.4 |

Table 5
Costing comparison between conventional methods and 3D printing applied to the optimized part

| Manufacturing methods | Cast molding | | Machining | | 3D printing | |
|---|---|---|---|---|---|---|
| Criterion | Initial part | Optimized part | Initial part | Optimized part | Initial part | Optimized part |
| Estimated cost/piece for manufacturing 100 pieces | 18.81 USD/Part | 56.36 USD/Part | 58.2 USD/Part | – | 199.1 USD/Part | 95.07 USD/Part |

## Conclusion

In this paper, we studied an engine-mounting bracket integrating the sustainability, topological optimization and additive manufacturing. First, we started by selecting the material with good mechanical performance: strength, stiffness, and less environmental impact. For this purpose, the material chosen is steel because it is a good compromise compared in terms of stiffness and sustainability to the other three materials (aluminum alloy, magnesium alloy and gray cast iron). Then, we optimized the topology of the engine mount by reducing its initial mass by 30% and keeping almost the same strength and durability of the support (stress and displacement almost identical to the initial part). Finally, the manufacturing process will be chosen through a life cycle analysis and an estimation of manufacturing costs for different processes: molding, machining and 3D printing.

From an environmental point of view, milling is better than sand molding while it is more expensive than molding. Casting molding and 3D printing will be compared by studying the manufacturing cost. For the manufacture of a part with a simple geometry (initial support), conventional manufacturing processes (sand molding or machining) are more appropriate because they are less expensive compared to 3D printing. However, if we have a complex geometry, such as that obtained by topological optimization, 3D printing is the most suitable.

To eco-design high-performance, durable, innovative, lightweight and less expensive products in terms of manufacturing process, it is important to integrate topological optimization and sustainability into the product development cycle. Thus, the combination of topological optimization, additive manufacturing and sustainability offers new perspectives in the development of simple or complex mechanical parts. The realization of a multi-objective optimization and the consideration of the maximum and fatigue loads are in progress for future publications.

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### Authors' contributions

Pr. Hicham FIHRI-FASSI: Conceptualization, Methodology, Supervision & Validation, Hadji Aniyou: Formal analysis, Software, Writing, Original draft, Review & Editing.

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### Declarations

Ethics Approval: The authors declare that the authors have no competing interests as defined by the journal, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Consent to Participate: This article has no involving human subjects. / Not applicable' for that section.

Consent for Publication: All authors have seen the manuscript and agree to its submission to MPER.

Competing Interests: The authors have no relevant financial or nonfinancial interests to disclose.

Conflict of interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

Replication of results: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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